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Geology of the Saint-Marcel valley metaophiolites (Northwestern Alps, Italy)

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ABSTRACT

The geological map of the Saint-Marcel valley at the scale of 1:20,000 illustrates the tectonic setting of metaophiolites from the southern Aosta Valley, in the Italian side of the Western Alpine belt. The map highlights the sharp contact between the metaophiolitic basement and its metasedimentary cover, which mainly consists of quartzites, marbles, and calc-schists. In spite of the Alpine tectonics, this contact is regarded as deriving from the original oceanic crust/sediments interface. Metaophiolites mostly consist of metabasalts hosting Fe–Cu sulphide mineralisations, characterised by high-pressure metamorphic imprint. These rocks likely represent the shallowest portion of the Tethyan oceanic lithosphere created near the axis of the slow-spreading ridge where hydrothermal fluid circulation was active. Selected key-sections through metasediments reveal a consistent internal lithostratigraphy, in spite of the pervasive metamorphic and tectonic reworking acting during the Alpine evolution. Metasediments reflect various sedimentation episodes starting from pelagic and proximal settings to the onset of the orogenic stage. The Saint-Marcel valley metasediments thus reflect a changing in the sedimentation environments through time and space during the overall geologic evolution.

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1. Introduction

The Saint-Marcel valley (Vallon de Saint-Marcel) is a dextral tributary of the Aosta Valley, in the Italian side of the Graian Alps, the NW segment of the Alpine chain (Figure 1(a)). The Saint-Marcel valley trends NS and extends for nearly 10 km from upstream, near the divide with the Cogne valley, to downstream near the village of Saint-Marcel (Figure 1(b)). The geology of the Saint-Marcel valley includes both oceanic and continental margin units (Figure 1(c)), derived from the Mesozoic Tethyan ocean and the Palaeozoic crust of the African margin, respectively, all involved in the Alpine accretionary complex (Polino, Dal Piaz, & Gosso, 1990). The oceanic units are represented by metamorphic eclogite-facies ophiolites and sediments (i.e. the Piemonte Nappe); the continental margin units correspond to the Austroalpine Mount-Emilius klippe. In the southern Aosta Valley, the Piemonte Nappe is commonly dominated by mantle-derived serpentinites, best exposed in the Mount-Avic massif (Dal Piaz et al., 2010; Elter, 1987; Fontana, Panseri, & Tartarotti, 2008; Fontana, Tartarotti, Panseri, & Buscemi, 2014; Panseri, Fontana, & Tartarotti, 2008), and of minor metabasalts and metasediments.

In the Saint-Marcel valley, the metaophiolites mainly consist of metabasalts hosting Fe–Cu sulphide-bearing mineralisations and a Mn-ore (Praz-Bornaz) related to oceanic hydrothermal processes (Brown, Essene, & Peacor, 1978; Martin, Rebay, Kienast, & Mével, 2008; Rebay & Powell, 2012; Selverstone & Sharp, 2013; Tumiati, Martin, & Godard, 2010; Tumiati, Godard, Martin, Malaspina, & Poli, 2015). Metabasalts are covered by a thick sequence of metasediments interpreted to be the relict sedimentary cover of the oceanic basement (Tartarotti, Martin, & Polino, 1986).

The geological map at 1:20,000 scale presented here derives from a compilation of maps originally realised at the 1:10,000 and 1:5000 scales, including PhD's and Master's Degree theses (Campana, 1988; Martin-Vernizzi, 1982; Tartarotti, 1988), implemented by a field mapping recently carried out by the authors of the present paper. This map represents the first geological detailed map produced in the Saint-Marcel valley. The aim of the present study is twofold: (i) to illustrate the tectonic setting of metaophiolites and overlying Austroalpine units, and, foremost, (ii) to describe the lithostratigraphy

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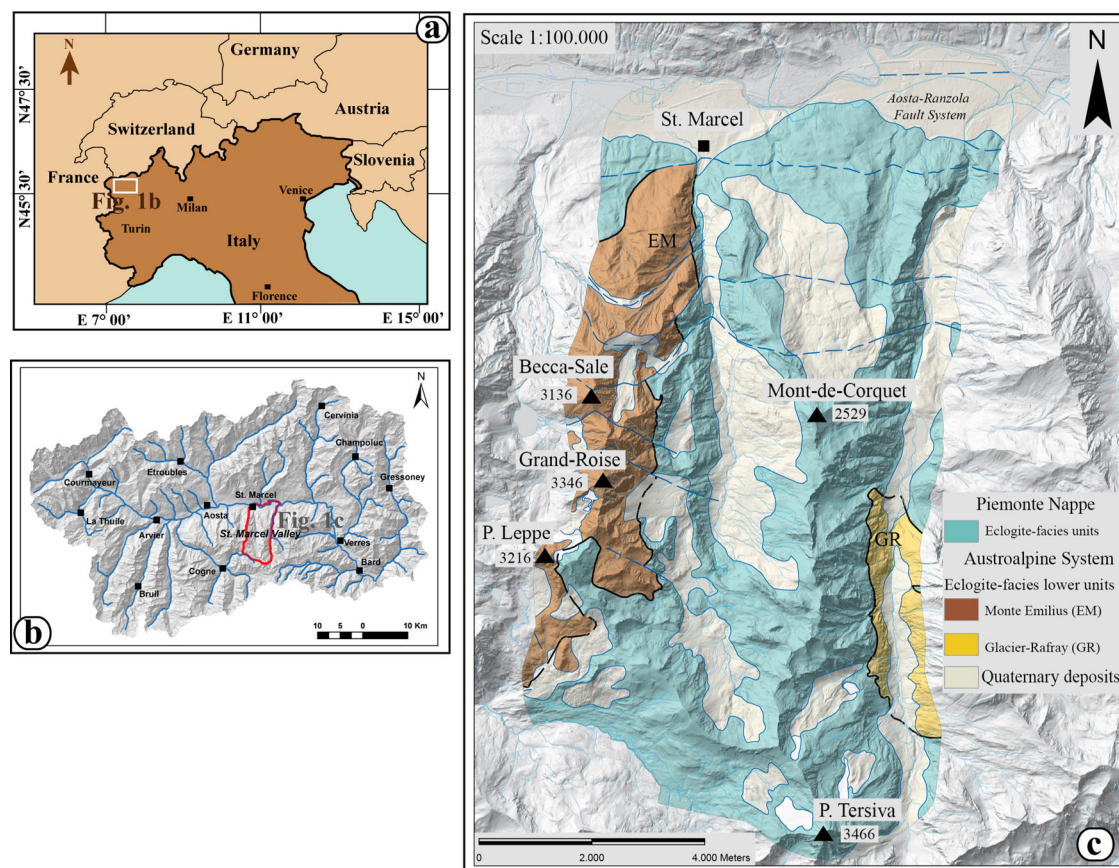


Figure 1. Geographic location and simplified geology of the study area. (a) Outline of northern Italy and neighbouring countries, and location of the Aosta Valley region (white rectangle). (b) Topography of the Aosta Valley region as obtained by LIDAR technique. The location of the mapped area across the Saint-Marcel valley is outlined by the red line. (c) Simplified geologic map of the Saint-Marcel valley.

of metasediments associated with metaophiolites. The map is integrated with five lithostratigraphic columns and two geological sections.

2. Geological setting

2.1. Western Alps metaophiolites

The Piemonte Nappe has been interpreted as the fossil oceanic lithosphere of the Mesozoic Tethys ocean, pinched between the Penninic (palaeo-Europe) and Austroalpine (palaeo-Africa) continental domains (see the tectonic sketch in the map; e.g. Deville, Fudral, Lagabriele, Marthaler, & Sartori, 1992; Dewey, Pitman, Ryan, & Bonnin, 1973; Laubscher, 1971; Martin, Tartarotti, & Dal Piaz, 1994; Polino et al., 1990). It consists of the Zermatt-Saas and the Combin units, which were defined in Switzerland and in the northern Aosta Valley on the base of the rock assemblage and metamorphism (e.g. Bearth, 1967; Bearth & Schwander, 1981; Dal Piaz, 1965; Dal Piaz & Ernst, 1978). The Piemonte Nappe extends southward to the eclogite-facies Monviso-Rocciavère-Lanzo units (Angiboust, Langdon, Agard, Waters, & Chopin, 2011; Balestro, Fioraso, & Lombardo, 2013; Castelli et al., 2014; Kienast & Pognante, 1988; Lombardo et al., 1978; Pognante &

Kienast, 1987), and to the blueschist-greenschist-facies Queyras-Ubaye ophiolitic units (e.g. Lagabriele, 1981; Lagabriele, Vitale Brovarone, & Ildefonse, 2015 and refs. therein).

In the southern Aosta Valley, metaophiolites include the eclogite-facies Zermatt-Saas and Grivola units, the blueschist- to greenschist-facies Combin and Aouilletta units, and the metasedimentary Cogne units (see the tectonic sketch in the map; Dal Piaz et al., 2010). These units have been distinguished on the base of their lithostratigraphy (Dal Piaz, Nervo, & Polino, 1979; Elter, 1960, 1971) and metamorphic conditions (Benciolini, Lombardo, & Martin, 1988; Castelli, 1985; Martin & Kienast, 1987; Martin & Tartarotti, 1989; Martin et al., 2008; Rebay & Powell, 2012). Metaophiolites and related cover sequences of the eclogite-facies units are dominated by mantle-derived (now serpentinitised) peridotites, metagabbros with metarodinitic dykes, mafic rocks, metatrandjemites, and by metasediments comprising metaradiolarites, marbles, and flysch-type calcschists (Beltrando, Lister, Hermann, Forster, & Compagnoni, 2008; Elter, 1987; Fontana et al., 2008; Martin & Tartarotti, 1989; Novo, Accotto, Nervo, & Pognante, 1989; Panseri et al., 2008; Tartarotti & Caucia, 1993; Tartarotti et al., 1986). The Grivola unit is thrust over the northern border of the Penninic

Gran Paradiso massif. The Zermatt-Saas and Grivola units are tectonically coupled with eclogite-facies slices of continental crust (i.e. the Mount-Emilius, Glacier-Rafray, Tour Ponton, and Acque Rosse tectonic units) pertaining to the Austroalpine domain (Dal Piaz et al., 1979, 2001; Dal Piaz, Lombardo, & Gosso, 1983; Pagnanelli, Compagnoni, Nervo, & Tallone, 1994; Pennacchioni, 1991), and showing an Alpine metamorphic evolution comparable with that of the eclogite-facies metaophiolites (Dal Piaz et al., 2001).

2.2. The Saint-Marcel valley metaophiolites

In the Saint-Marcel valley, metaophiolites consist of eclogite-facies Fe–Ti- and Mg-metagabbros, glaucophanites with garnet and lawsonite (now pseudomorphed) enclosing eclogite boudins, associated with garnet-chloritoid-glaucophane-chlorite-bearing schists, and minor talcschists (Figures 2(a,b); see also Krutow-Mozgawa, 1988; Martin & Tartarotti, 1989; Martin et al., 2008; Tartarotti, 1988; Tartarotti & Caucia, 1993). In the northern part of the valley, the eclogite-facies mineral assemblages are better preserved than in the southern part. The eclogitic imprint is of Eocene age (45–42 Ma) like in the overlying Austroalpine tectonic units (49–40 Ma; Dal Piaz et al., 2001).

In the northern Saint-Marcel valley, the ductile early-alpine structures are still recognisable and represented by dm- to m-sized isoclinal folds with N–S trending sub-horizontal axes and steeply dipping axial planes. These represent the main D_2 structures, which fold earlier foliations. The main foliation (S_2) strikes N–S and dips 60°–80° to W. It has been interpreted as an eclogite-facies foliation defined by glaucophane, garnet, and omphacite (Martin & Tartarotti, 1989). The eclogite boudins within glaucophanite preserve D_1 eclogite structures (see Figure 2(b)).

Relics of an earlier deformation pre-dating the eclogite peak have been recognised only in the core of zoned garnets of the glaucophanites, chlorite-schists, and quartzites (Tartarotti & Caucia, 1993), whereas the D_1 structures are commonly absent in the matrix due to the dominant mylonitic character of the D_2 deformation phase. The D_2 phase was superimposed by greenschists-facies D_3 phase characterised by folds with 20°–60° steep axial planes and N–S trending axes (Martin & Tartarotti, 1989).

Estimation of the peak P – T conditions for the Saint-Marcel valley eclogites provides $T = 550 \pm 60^\circ\text{C}$ and $P = 2.1 \pm 0.3$ GPa (Martin et al., 2008). These P – T values are higher than those previously obtained in the Saint-Marcel valley ($T_{\text{max}} = 550 \pm 20^\circ\text{C}$; $P_{\text{max}} = 1.2 \pm 0.1$ GPa performed by Martin & Tartarotti, 1989 on eclogite boudins; $T_{\text{max}} = 500^\circ\text{C}$; $P_{\text{max}} = 1.4$ GPa obtained on eclogite Mn-assemblages by Brown et al., 1978; Martin & Kienast, 1987; Mottana, 1986), but lower than those obtained in the Zermatt-Saas

metaophiolites from Zermatt (e.g. Bucher, Fazis, De Capitani, & Grapes, 2005: $T = 550$ – 600°C , 2.5–3.0 GPa) and for the subduction-related metamorphic peak in the Lago di Cignana unit (e.g. Frezzotti, Selverstone, Sharp, & Compagnoni, 2011: ca. 600°C , ≥ 3.2 GPa; Groppo, Beltrando, & Compagnoni, 2009: 400 – 650°C , 1.0–1.7 GPa; Reinecke, 1998: 600 – 630°C , 2.7–2.9 GPa). Oceanic metasediments associated with metaophiolites occur on both sides of the Saint-Marcel valley, and consist of Mn–Fe-rich metacherts, marbles and micaceous calcschists (Martin & Kienast, 1987; Tartarotti et al., 1986). Sulphide- and Mn-rich ore deposits are associated with metabasalts and metasediments exposed in the Saint-Marcel valley (e.g. sulphide deposit: Bois de Fontillon-Servette district, see Figure A in the map; Mn-ore deposit: near Praz-Bornaz, see the map). The Saint-Marcel valley metaophiolites are interpreted to represent the shallowest part of the Tethyan oceanic lithosphere, that is, the crustal portion created not far from the ridge axis where hydrothermal vents were active, and its pelagic sedimentary cover sequence.

2.3. Key-sections lithostratigraphy

From north to south along the Saint-Marcel valley, five key-sections were selected to illustrate the lithostratigraphy of the metasedimentary cover sequence, and its relation with the ophiolitic basement: the Bois de Fontillon-Servette, Mont-Roux, Mont-de-Corquet, and the Pointe-de-Plan-Rue sections (located on the eastern side of the valley); the Rouallaz section located on the western side of the valley. These sections are characterised by a well defined, often sharp, contact between metaophiolite and metasediments, with scarce repetition of metaophiolitic layers within metasediments. The present thickness of the metasediments increases from a few metres up to 800 m going from the north to the south along the valley.

The Bois de Fontillon-Servette section is located in the northern valley (Figure A in the map). The ophiolitic basement is well exposed near the Fontillon Damon farm, along a N–S-trending ridge (*roche moutonnée*), about 800-m long and 70-m high. Rocks are garnet-bearing glaucophanites including cm- to dm- sized eclogite boudins (Figures 2(a–c)). Layers of glaucophanite alternate with layers of garnet-chloritoid-glaucophane-bearing chlorite-schists and minor talcschists (see Figure 2(a)), as a result of tectonic transposition of basalt and basalt-derived rocks (Alpine D_2 phase; Martin & Tartarotti, 1989) that occurred under eclogite-facies metamorphic conditions. The Bois de Fontillon ophiolitic basement continues southwards to the Servette mining district, where it hosts Cu–Fe sulphide ores (i.e. the Servette and Chuc deposits; Castello, 1981; Dal Piaz & Omenetto, 1978; Martin et al., 2008). Metaophiolites are here associated with a metasedimentary cover

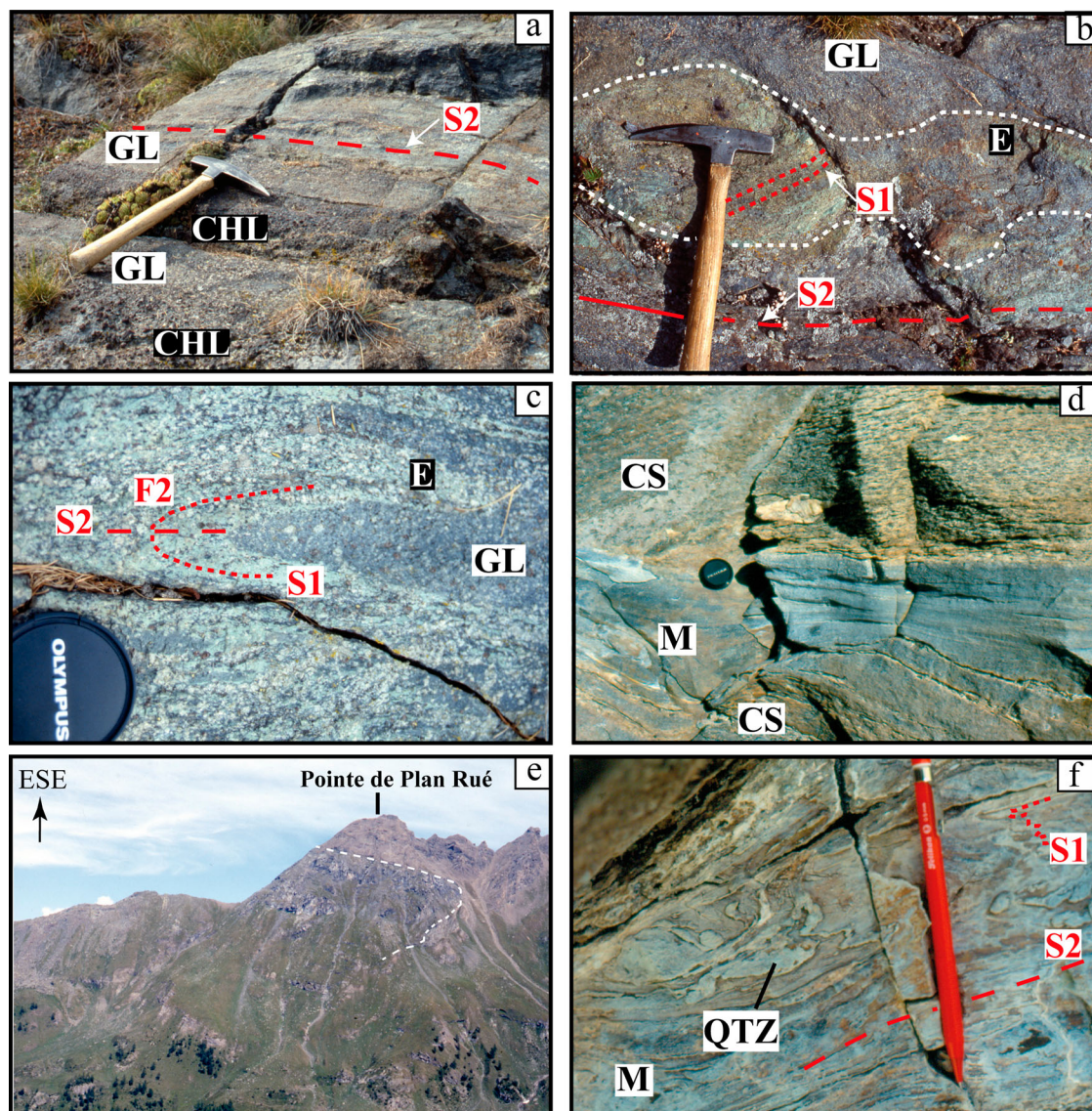


Figure 2. Examples of the metaophiolites in the Saint-Marcel valley. (a) Garnet-bearing glaucophanites (GL) interlayered with garnet-chloritoid-glaucophane-bearing chlorite-schists (CHL) and minor talcschists. Fontillon outcrop (northern Saint-Marcel valley; long. 7°27'09.36"E, lat. 45°42'32.08"N, alt. 1600 m a.s.l.). The S_2 foliation trace is also shown. (b) Mafic eclogite boudins (E) included within glaucophanites of the Fontillon outcrop. The trace of older S_1 foliation within the eclogite boudin is shown in relation to the S_2 foliation. (c) Tight isoclinal folds marked by eclogite (E)/glaucophanite (GL) contact. S_1 and S_2 traces are shown (Fontillon outcrop). (d) Layer of fine-grained pale-grey impure marble (M) bounded by carbonate-rich micaceous quartzite (Mont-Roux outcrop; long. 7°28'04.41"E, lat. 45°41'26.25"N, alt. 2300 m a.s.l.; see also Figure B in the [Main Map](#)). (e) Panoramic view of the eastern side of the Saint-Marcel valley dominated by the Pointe-de-Plan-Rue peak (long. 7°28'05.29"E, lat. 45°39'43.59"N, alt. 2882.9 m a.s.l.). An hectometric recumbent fold is marked by the contact between metasediments and metaophiolites (white dashed line; see also Figure D in the [Main Map](#)). (f) Example of micaceous quartzite folded within marble (the outcrop is located between the Pointe-de-Plan-Rue peak and the Grand Crête peak, along the eastern side of the Saint-Marcel valley; long. 7°28'19.93"E, lat. 45°39'36.90"N, alt. 2860 m a.s.l.).

sequence, about 10 m-thick, made of (from bottom to top) fine-grained metarodingite (probably original basalt), garnet-bearing micaceous quartzites including clinopyroxene, blue-amphibole, and relict cummingtonite included in garnet (Tartarotti & Caucia, 1993). Actinolite-schists occur at the contact between metasediments and metaophiolites (see Figure A in the map).

The Mount-Roux section (Figure B in the map) is characterised by a ca. 100 m-thick metasedimentary sequence lying on top of Mg-metagabbros and prasinities (i.e. fine-grained albite-actinolite-chlorite-

epidote-bearing rocks deriving from metabasalt or metagabbro) enclosing eclogite boudins. The contact between mafic rocks and metasediments is marked by actinolite-schists (bearing Cr-rich mica). Metasediments consist of (from bottom to top; see Figure B in the map) micaceous quartzites, impure marbles (Figure 3(a)), manganiferous quartzites (Figure 3(b)), carbonate-rich micaceous quartzites (Figures 3(c,d) alternating with fine-grained pale-grey marbles (Figure 3(e); see also Figure 2(d)). This sequence is followed by calcschists with a typical flysch-like appearance consisting of siliceous marly limestone alternating with

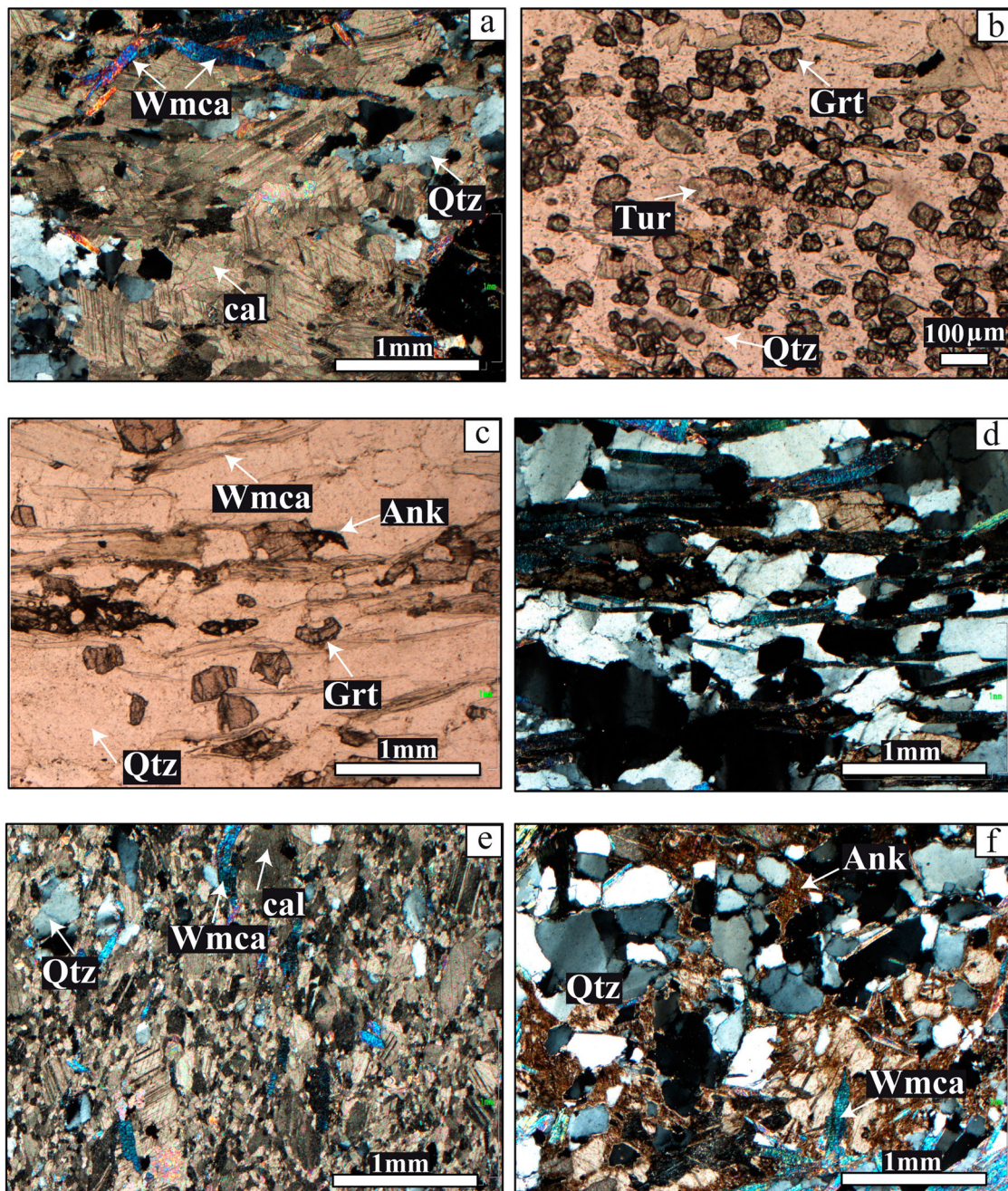


Figure 3. Photomicrographs of the Saint-Marcel valley metasedimentary sequence. All samples are from the Mount-Roux section (see Figure B in the map). (a) Impure marble consisting of calcite, polycrystalline quartz, white mica, garnet, zoisite. (b) Manganiferous quartzite consisting of quartz, garnet, tourmaline, white mica, chlorite. (c, d) Carbonate-rich micaceous quartzite consisting of quartz, white mica, garnet, Fe-rich carbonate, clinozoisite alternating with fine-grained pale-grey marble consisting of calcite, polycrystalline quartz, and white mica. (e, f) Calcschist made of carbonate, polycrystalline quartz, white mica, garnet from the micaceous portion of flysch-like calcschists; relict isoclinal fold hinges are visible (Mount-Roux section). Photomicrographs a, b, d, e were made under cross-polarised light; photomicrographs b, c under plane-polarised light. Mineral abbreviations according to [Stivola and Schmid \(2007\)](#).

shaly beds ([Figure 3\(f\)](#); see also Figure BIII in the map), and minor quartz-carbonate-rich micaschists ('terrigenous metasediments' in the legend of the map) and micaceous quartzites. Calcschists may also include mafic layers or boudins.

The Mont-de-Corquet section ([Figure C](#) in the map) is characterised by a 150 m-thick metasedimentary sequence making a cliff along the eastern side (right) of the Saint-Marcel valley. The metaophiolitic basement is not exposed, although amphibolites are

interlayered within metasediments. The cover sequence is here overturned and consists (from top to bottom) of manganiferous metacherts, green micaceous quartzites, micaceous marbles, and flysch-type calcschists.

The Pointe-de-Plan-Rue section ([Figure D](#) in the map) includes a metasedimentary sequence cropping out on the overturned limb of a hectometric recumbent fold exposed on the eastern side of the valley ([Figure 2 \(e\)](#)). The core of the fold is made of glaucophanite rich

in pseudomorphs after lawsonite. Metasediments are represented by micaceous quartzites (Figure 3(f)), manganiferous quartzites, impure marbles, carbonate-rich micaceous quartzites, quartz-chloritoid-rich micaschists covered by marbles and flysch-type calcschists. On the Plan-de-Rue peak, calcschists reach a thickness of about 50 m (see Figures DI, DII in the map and Figure 2(e)).

The Rouallaz section (Figure E in the map) crops out on the western side of the Saint-Marcel valley, below the tectonic contact separating the Austroalpine Mount-Emilius klippe from the metaophiolites, here consisting of garnet-bearing glaucophanites with relict pillow structures. The metasedimentary sequence is overturned (see Figure EIII) and is made of (from top to bottom) micaceous quartzites, amphibole-chlorite-rich quartzites, flysch-type calcschists alternating with graphitic micaschists and marbles.

The lithological assemblage of quartzites, marbles, and flysch-type calcschists (marly limestones alternating with shaly beds) observed in the Saint-Marcel valley strongly recalls the classical supra-ophiolitic sedimentary sequence described in the Northern Apennine, consisting of cherts and/or radiolarite, 'Calpionella Limestone', and 'Palombini Shale' formations (e.g. Abbate, Bortolotti, & Principi, 1980; Decandia & Elter, 1972) whose age ranges from Late Jurassic to Palaeocene (Chiari, Marcucci, & Principi, 2000; Maroni, Monechi, Perilli, Principi, & Treves, 1992 and references therein). By analogy, the supra-ophiolitic sedimentary sequences described in the *Schistes Lustrés* of the Cottian Alps have been attributed to a similar time range (Lemoine, 1971; Polino & Lemoine, 1984; see review in Deville et al., 1992).

Summing up, the Saint-Marcel valley metasedimentary sequence starts, from bottom to top, with manganiferous quartzites followed by fine-grained, impure marbles. These two lithologies are associated with several types of quartzites and micaschists. This rock assemblage is then covered by flysch-type (like the Palombini shales) calcschists with variable thickness, from tens to hundreds metres, as observed along the Mount-Roux-Grand Crête ridge (see the map). The contact between the quartzites/micaschists series (the thickness of which never exceeds 10–15 m) and the flysch-type calcschists is often marked by terrigenous calcschists or by graphitic calcschists, as observed for example in the Rouallaz section.

3. The sulphides and manganese mines of the Saint-Marcel valley and their anthropic significance

The Fe–Cu hydrothermal sulphide deposits of Bois de Fontillon-Servette and Chuc-Eve Verda spring and the famous Praz-Bornaz (or Praborna) Mn mine, now abandoned, have been exploited since the seventeenth

century or since the Roman time. The ruins of the old foundry of Treves (lat. 45°42.444'N, long. 7°27.432'E, alt. 1672 m) and huge amounts of slags derived from the Servette ore processing (long. 7°27.304'E, lat. 45°42.449'N, alt. 1659 m) can be still observed in the Druges-Damon area, in the Northern Saint-Marcel valley. The slags are composed of fayalite, wustite, spinel, sulphides, and interstitial glass and include carbonised wood. The ¹⁴C datation of a piece of carbonised wood (*Picea excelsa*) enclosed in a slag of Servette suggests exploitation in the Middle Age (1120 ± 40 BP) (GX-29281; Tumiatì et al., 2005). Near the intersection with the old 'Strada Cavour' a large heap of slags (lat. 45°41.660'N, long. 7°27.134'E, alt. 1734 m) occurs. These slags have given a more recent age (<100 B.P.; GX-29282; Tumiatì et al., 2005), probably referred to the period when Servette was exploited by the Challant family, as recorded by Nicolis de Robilant (1786–87; see also Cesti, 1978; Lorenzini, 1998; Martin, Godard, & Rebay, 2004).

The Cu–Fe Chuc mine is located on the left side of the river at altitudes between 1283 and 1443 m (see the map); it has been in activity from 1854 to 1950 (Lorenzini, 1998). The village of Chuc is located on the right side of the river (long. 7°26.863'E, lat. 45°42.044'N, altitude 1422 m; not shown in the map) and now consists of ruined houses. A few hundreds of metres below Chuc, the pathway crosses a small river that descends from Servette to the Eve Verda spring (long. 7°26.940'E, lat. 45°42.094'N, altitude 1371 m). The water, when saturated in Cu, pours out a blue gel that covers the pebbles on the river bed. This blue gel was described by Saint-Martin de La Motte (1784–85), de Saussure (1796, t. 4, p. 459) and Prosio (1903). The gel is made of almost amorphous Cu hydroxide (woodwardite), which likely precipitates during a change of pH (Tumiatì, Godard, Masciocchi, Martin, & Monticelli, 2008).

The ancient Praz-Bornaz (or Praborna) mine (long. 7°26.968'E, lat. 45°40.774'N, alt. 1894 m) was intensively exploited by the Challant and Davise families during the seventeenth and eighteenth centuries (archives of the Aosta Province bureau). Braunite was used by the glassmakers of Murano, near Venice to fade glass, thanks to the relatively high electronegativity of Mn. The ore consists of manganiferous quartzites, including a 4–8 m-thick boudinaged layer rich in braunite (Mn²⁺ Mn³⁺SiO₂) associated with the glaucophanites and eclogites.

The Praborna ore is the type locality for several rare Mn minerals, such as violan, a semiprecious violet-blue Mn-bearing clinopyroxene; piemontite; alurgite, the Mn-bearing variety of muscovite; romeite, a complex oxide of Sb, Mn, and Fe greenovite, a variety of titanite; strontiomelane. Many other manganese minerals have been observed: braunite, garnets (spessartine, blythite, calderite, etc.; Martin & Kienast, 1987; Martin-Verzizzi, 1982; Tumiatì et al., 2010, 2015); Mn-bearing

augite, jadeite and chloromelanite; rhodonite; K-F-Mn-richite; thulite hollandite, and rhodochrosite.

4. Methods

The map is at 1:20,000 scale and encompasses an area of about 110 km². The geological map derives from original fieldwork including (i) a compilation of maps originally realised at the 1:10,000 and 1:5000 scales during PhD's and Master's Degree theses by S. Martin, R. Campana, and P. Tartarotti; (ii) additional maps recently performed by the authors at the 1:10,000 scale. Cross-sections are oriented perpendicular to the overall trend of the main structures.

Geological mapping was performed using topographic maps (*Carta Tecnica Regionale*) released by the *Regione Autonoma Valle d'Aosta – Assessorato territorio e Ambiente* (Aut. n. 1611 del 17/07/2015) and represented on a vector topographic map derived from the CTRN (*Carta Tecnica Regionale Numerica* 1:25,000; Coordinate System represented in meters ED50-European Datum 1950, UTM Zone 32 Nord). Quaternary deposits have been mapped by original fieldwork supported by photointerpretation of aerial images of the Regione Valle d'Aosta.

5. Discussion and conclusions

Field work data allowed us to elaborate the geological map provided at the scale of 1:20,000 with two geological sections, and to characterise some significant lithostratigraphic series. Petrographic observations also furnish further data on the nature and composition of metasedimentary rocks covering the metaophiolites. We summarise in the following the main results and highlight some topic of research to be developed in the future.

The metaophiolitic basement mostly consists of metabasalts showing Alpine high-pressure metamorphic imprint, and hosting Fe–Cu sulphides ores. These rocks likely represent the shallowest portion of the Tethyan oceanic lithosphere characterised by lava flows, pillow basalts, and derived rocks. The abundant Fe–Cu and Mn-rich ore deposits characterising the Saint-Marcel valley metaophiolites indicate that the corresponding portion of oceanic lithosphere was probably created near the axial part of the ocean ridge where hydrothermal fluid circulation was active. The close association of metabasalts and Fe–Cu–Mn mineralisations make the Saint Marcel valley metaophiolites almost unique among the eclogite-facies Alpine metaophiolites. A similar association has been described only in the eclogite-facies Monviso metaophiolites, which preserve the signature of mid-ocean ridge hydrothermal alteration (e.g. Nadeau, Philippot, & Pineau, 1993) and mineralisations (e.g. Rolfo et al., 2015 and refs. therein). By contrast, the Saint-Marcel

valley metaophiolites strongly differ from other Alpine metaophiolites (e.g. the Platta and Tasna ophiolites) which are located in a palaeogeographic position consistent with ocean-continent transition zones (i.e. 'OCT' settings; e.g. Manatschal & Müntener, 2009). The sharp contact between the Saint-Marcel valley metaophiolites and metasediments, starting with manganiferous quartzites, indicates the partial preservation of the original oceanic stratigraphy in spite of the Alpine deformation. This contact may be regarded as a marker for reconstructing the lithostratigraphy within the metasedimentary cover sequence. The basal manganiferous quartzites may represent the metamorphic analogues of pelagic sediments rich in Mn-oxides, like those found in hydrothermal Mn-deposits distributed in modern oceans (e.g. Usui & Someya, 1997; see also discussion in Tumiati et al., 2010). The Praborna Mn-rich deposit in the Saint-Marcel valley has been interpreted as the high-P metamorphosed equivalent of the Jurassic Mn-rich cherts (e.g. Tumiati et al., 2010).

Similar lithostratigraphic settings have been described in the blueschist-facies metaophiolites of the French Cottian Alps (namely, the Queyras region; e.g. Lagabriele, 1994), in the eclogite-facies metaophiolites of the Monviso complex (namely, the Costa Ticino series; Lombardo et al., 1978; the Baracun series; Lagabriele & Polino, 1988), and in the blueschist- and eclogite-facies metaophiolites of Corsica (e.g. Vitale Brovarone, Picatto, Beyssac, Lagabriele, & Castelli, 2014 and refs. therein) where the ophiolitic basement is stratigraphically associated with radiolarian cherts, marbles, and calcschists. In these regions, however, and particularly in the Queyras, the metasedimentary sequence is often characterised by numerous intercalations of ophiolitic arenites, breccias, and olistoliths which are not observed in the Saint-Marcel valley.

The Saint-Marcel valley metaophiolites also differ from many sequences of the Piemonte Nappe (e.g. Lagabriele et al., 2015 and refs. therein; Tartarotti, Festa, Benciolini, & Balestro, 2015; Tricart & Lemoine, 1991) for not showing the direct juxtaposition of oceanic sediments upon serpentinitised peridotites and associated gabbroic intrusions. Comparisons with modern slow-spreading oceans have lead many authors to interpret the primary association of serpentinites and sediments as a signature of tectonic mantle denudation in the Jurassic Tethys (e.g. Lagabriele & Cannat, 1990; Lemoine, Boillot, & Tricart, 1987; see review in Lagabriele, 2009). Such model is supported by the occurrence in the Alpine metaophiolites of thick shear zones recently interpreted as a record of oceanic detachment faults (e.g. Balestro, Festa, Dilek, & Tartarotti, 2015; Balestro, Festa, & Tartarotti, 2014; Festa, Balestro, Dilek, & Tartarotti, 2015; Manatschal et al., 2011).

The Saint-Marcel valley metasedimentary sequence is reconstructed from the key-sections described in

this paper, and consists, from bottom to top of: (i) a basal series characterised by manganiferous quartzites commonly grading to fine-grained, impure marbles; (ii) an intermediate series consisting of micaceous quartzites and micaschists; (iii) a top part made of three different rock types: quartz-rich calcschists ('ter-rigenous metasediments' in the map legend), graphitic calcschists, and flysch-type calcschists ('undifferentiated calcschist' in the map legend). In the upper Saint-Marcel valley, as in the nearby Pointe Tersiva and Rosa dei Banchi peaks, these upper calcschists reach a thickness of a few hundred metres.

In spite of metamorphism and the absence of fossiliferous contents (the only age constraint is the Eocene age of the eclogite-facies metamorphism in the metaophiolites; Dal Piaz et al., 2001), we infer that the Saint-Marcel metasedimentary sequence records the tectonosedimentary events of the Tethyan basin, from oceanisation to subduction and collision in the Alpine belt. Based on correlations with other sections of the Western Alps (see the synthesis paper by Deville et al., 1992), and comparison with the unmetamorphosed stratigraphic sequences in the Northern Apennines (e.g. Abbate et al., 1980; Marroni et al., 1992), we suggest that the Saint-Marcel sediments were deposited in different environments during at least three main diachronous events. The basal series was deposited in the abyssal plain of the Tethys ocean during the Middle to Late Jurassic (e.g. Chiari et al., 2000; De Wever & Caby, 1981), when oceanic spreading was still active. The overlying series consisting of micaceous quartzites and micaschists may derive from detrital material delivered either by the proximal passive continental margin during the extensional stage or by the overriding continental plate after the onset of subduction. The age of this series cannot be easily constrained, since it differs from other sequences of the Western Alps (e.g. Valais, French-Italian Alps) or Apennines showing a similar stratigraphic position, which are commonly characterised by abundant detrital deposits and olistoliths of both continental and ophiolitic nature. The sequences from the Valais and French-Italian Alps have been attributed to early episodes of the Alpine compressive tectonics occurred during the early Late Cretaceous (e.g. Fudral, Deville, & Marthaler, 1987; Lagabriele & Polino, 1988; Lemoine et al., 1984; Marthaler, 1984). The equivalent sedimentary units in the Apennines are represented by the 'Casanova' complex of Cenomanian-Turonian age (e.g. Abbate, Bortolotti, & Principi, 1984; Decandia & Elter, 1972).

The Saint-Marcel uppermost calcschists are interpreted as syn-orogenic flysch. These rocks although completely devoid of ophiolitic detrital material, likely correspond to the metaflysch series occurring on top of the *Schistes Lustrés* nappe of the French-Italian Alps (see Deville et al., 1992), and possibly to the 'Flysch a

Helmintoides' formation in the Apennines dated Upper Cretaceous (e.g. Decandia & Elter, 1972).

In conclusion, the Saint-Marcel valley represents a meaningful case for the understanding of the origin and evolution of the Alpine metaophiolites. Among metaophiolites involved in the Alpine subduction, those of the Saint-Marcel valley are particularly rich in basaltic rocks which also host sulphides and manganese mineralisations. This assemblage can be interpreted as deriving from a mid-ocean ridge segment affected by hydrothermal fluid circulation. Moreover, the Saint-Marcel valley metasediments refer to sedimentation ranging from pelagic and proximal environments to the onset of the orogenic stage. Given the absence of any available age for these sequences, and taking into account the effect of pervasive tectonic transposition, we suggest that the different types of metasediments could reflect a changing in the sedimentation environments through time as well as through space during the overall geologic evolution. Indeed, the Alpine deformation could have contributed to juxtapose sedimentary sequences originated in different, even if adjacent, environments. Further structural and petrographic studies on the Saint-Marcel valley metasediments, integrated with data from present-day comparable settings are needed to better constrain the nature of the supra-ophiolitic cover sequence.

Software

The geological dataset has been implemented and validated in the ESRI® GIS environment (ArcGis®). The geometric primitives and alphanumeric attributes of interest for the map production have been extracted in shp file format from the ESRI® geodatabase. These features have been imported into the Adobe Illustrator® environment through MAPublisher®. This allowed keeping intact, readable, and editable both the geometric/spatial component and the descriptive part of these features. Finally, we have used Adobe Illustrator® for the cartographic layout and letterpress, for all drawings and photo assemblage.

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